



LITHIUM ION BATTERIES ON 2003 MARS EXPLORATION ROVER

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The Mars Exploration Rover

An in situ science mission to Mars

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Salient Features

- Two identical landers launched in May-July 2003 on Delta II 7925 Launch vehicle.
- Targeted to two sites on Mars, landing January and February 2004
- Mars Pathfinder lander architecture
- Each delivers a highly capable rover carrying the Athena payload

On a mast:

Camera and spectrometer

On a 5-degree-of-freedom robotic arm:

Spectrometers, microscopic imager, rock abrasion tool

On the rover:

Magnet array, calibration targets

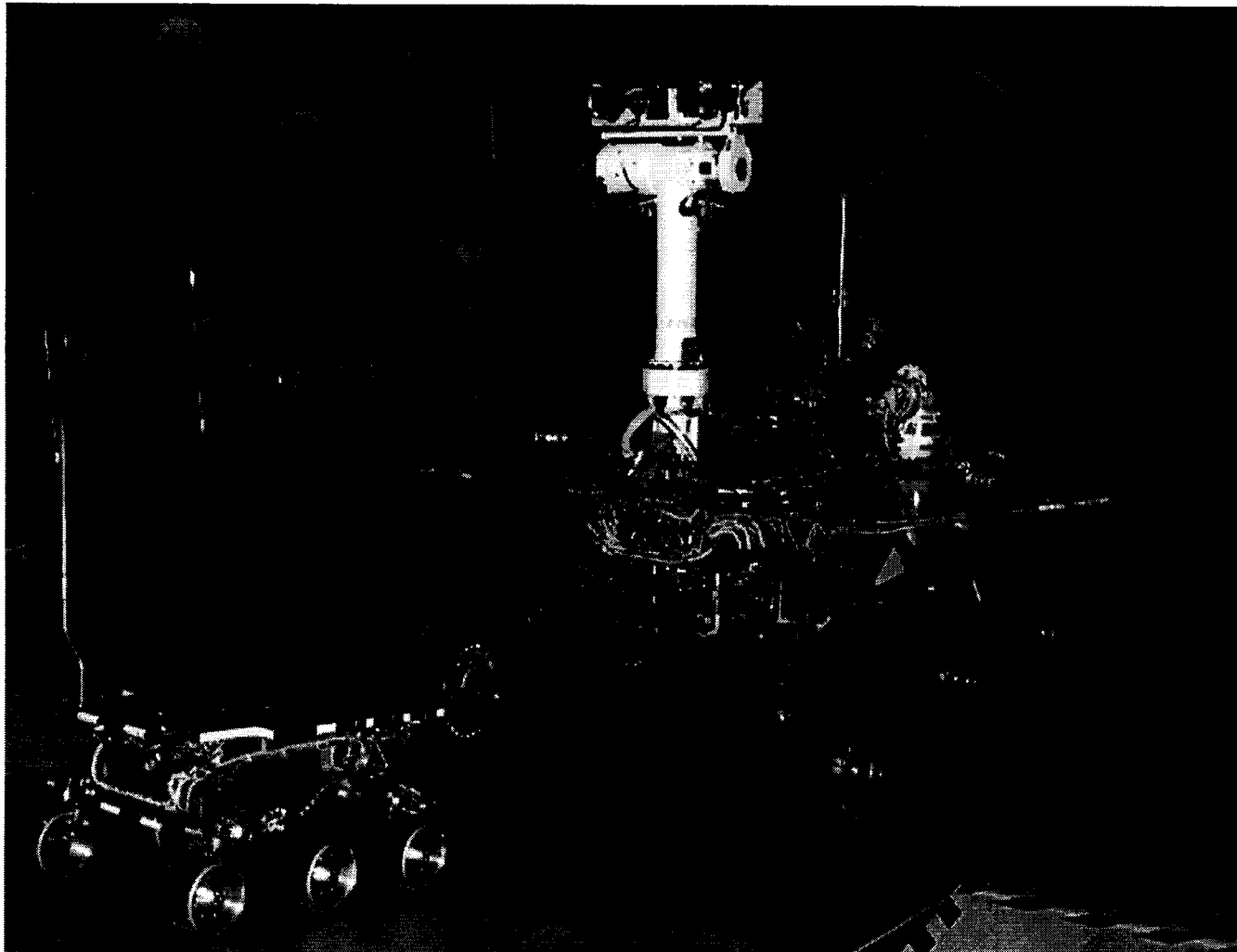
- Two surface missions with an integrated traverse distance of greater than 600 meters over the 90-sol mission lifetime with a possible extended mission.





2003 MER vs. 1995 Sojourner

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Mission Objectives



- **Science**

- Search for and characterize a diversity of rocks and soils that hold clues to past water activity
- Investigate landing sites which have a high probability of containing physical and/or chemical evidence of the action of liquid water
- Determine the distribution and composition of minerals, rocks, and soils
- Characterize mineral assemblages and textures in the geologic context
- Identify and quantify iron-bearing minerals indicating aqueous processes
- Extract clues from geologic investigation related to liquid water to assess whether past environments were conducive for life

- **Program**

- Demonstrate long-range traverse capabilities by mobile science platforms
- Demonstrate complex science operations with two mobile laboratories
- Validate the standards, protocols, and capabilities of the orbiting Mars communications infrastructure



Science instruments (Athena Heritage)



- **Two remote sensing instruments mounted on Pancam (Panoramic Camera) Mast Assembly to select target.**
 - **Mast mounted Stereo cameras with color filters on pan/tilt gimbal.**
 - **Mini Thermal Emission Spectrometer (Mini-TES) Near and mid-IR point spectrometer for mineralogy of rocks.**
- **In-Situ Payload Elements**
 - **Mossbauer Spectrometer for mineralogy of Fe-bearing minerals in rocks.**
 - **Alpha Particle X-ray Spectrometer (APXS) for elemental chemistry.**
 - **Microscopic Imager (MI) for environmental conditions under which geologic materials formed.**
 - **Rock Abrasion Tool (RAT) to penetrate thro' rock dust and surface alteration.**
- **The front HAZCAMs provide imaging of workspace for ground planning of instrument deployments**



Rover Capabilities



Avionics

- Rad6000 Flight Computer (20Mhz, 128MB DRAM)
- 256MB Non-volatile FLASH data storage
- Analog, digital, serial IO
- Motor control for 36 brushed motors, 4 stepper motors & 4 brushless motors

Power

- Triple-Junction GaInP/GaAs/Ge cell deployable solar arrays
- (2) 8A-hr Li-Ion rechargeable batteries
- Power conversion and distribution

Navigation Sensors

- Mast mounted stereo navigation cameras - NAVCAMs - Front & Rear stereo hazard cameras - HAZCAMs - with 120deg FOV) SUNCAM (mounted on HGA gimbal)
- 6DOF IMU

Telecom

- Direct to Earth Communication (X-band) with fixed Low Gain and gimbaled High Gain Antennas
- Orbiter relay communication (UHF) with fixed monopole antenna

Mobility System

- 6 wheel Rocker-Bogie mechanism with 25cm diameter wheels
- 5cm/s top speed (~0.6m/minute under autonomous navigation)

Thermal

- Aerogel insulated Warm Electronics Box
- Resistive heaters on external motors/cameras and internal components
- Radioisotope heating units (RHUs)
- Battery thermal switch heat rejection system
- SSPA Loop Heat Pipe heat rejection system



Flight System Configuration

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Cruise Stage

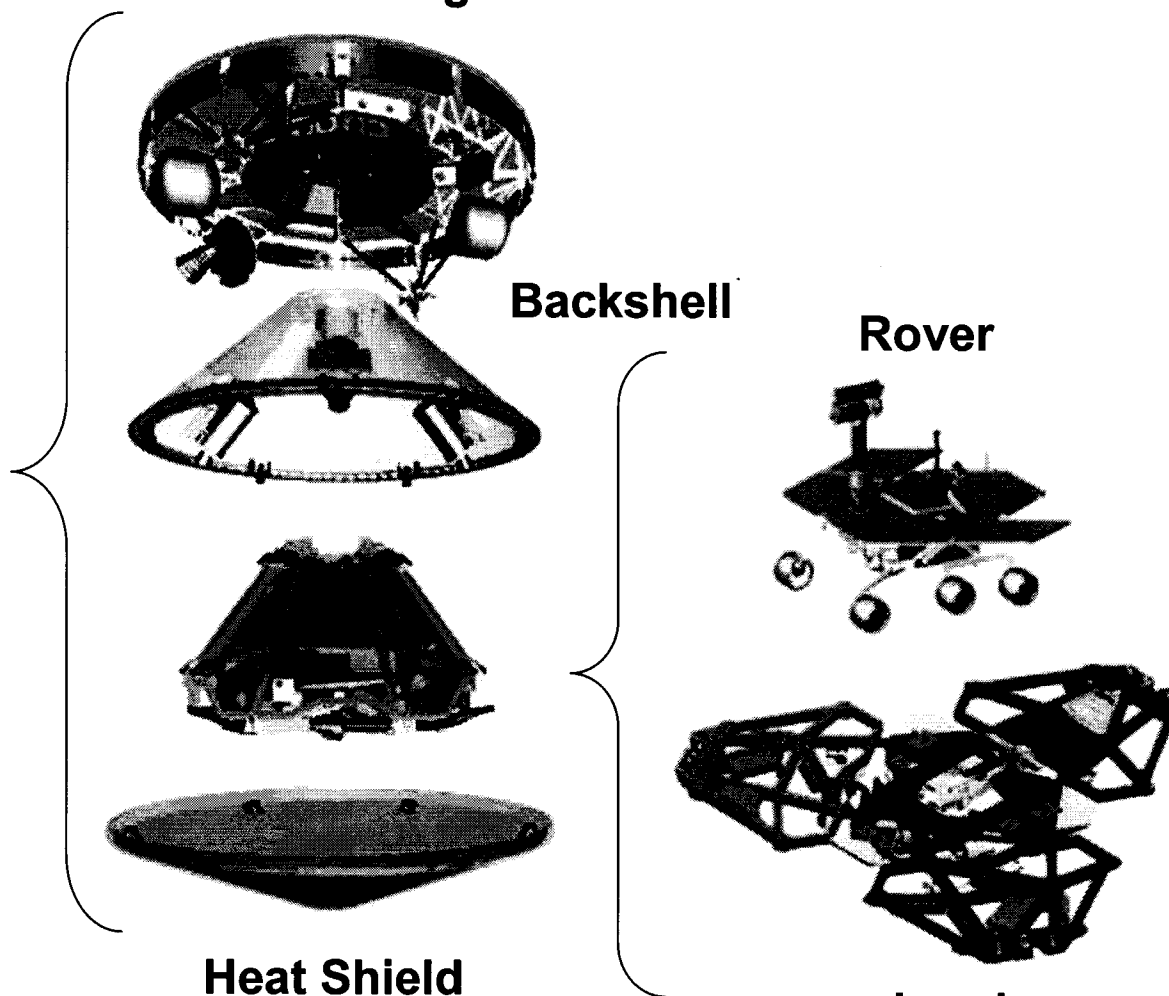
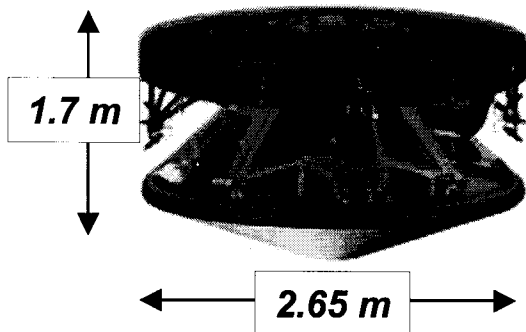
Flight System

Backshell

Rover

Heat Shield

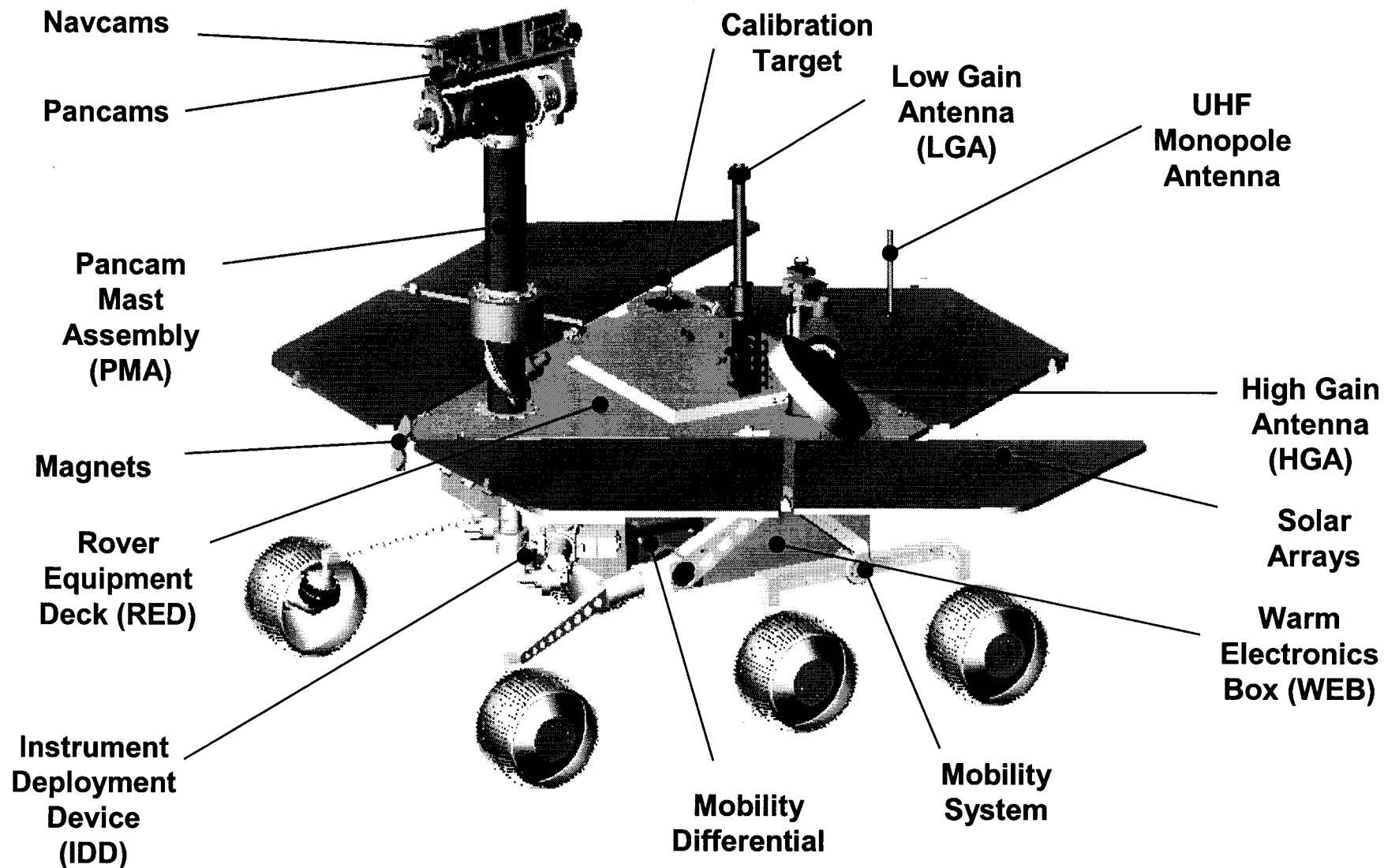
Lander





Rover Configuration - Deployed

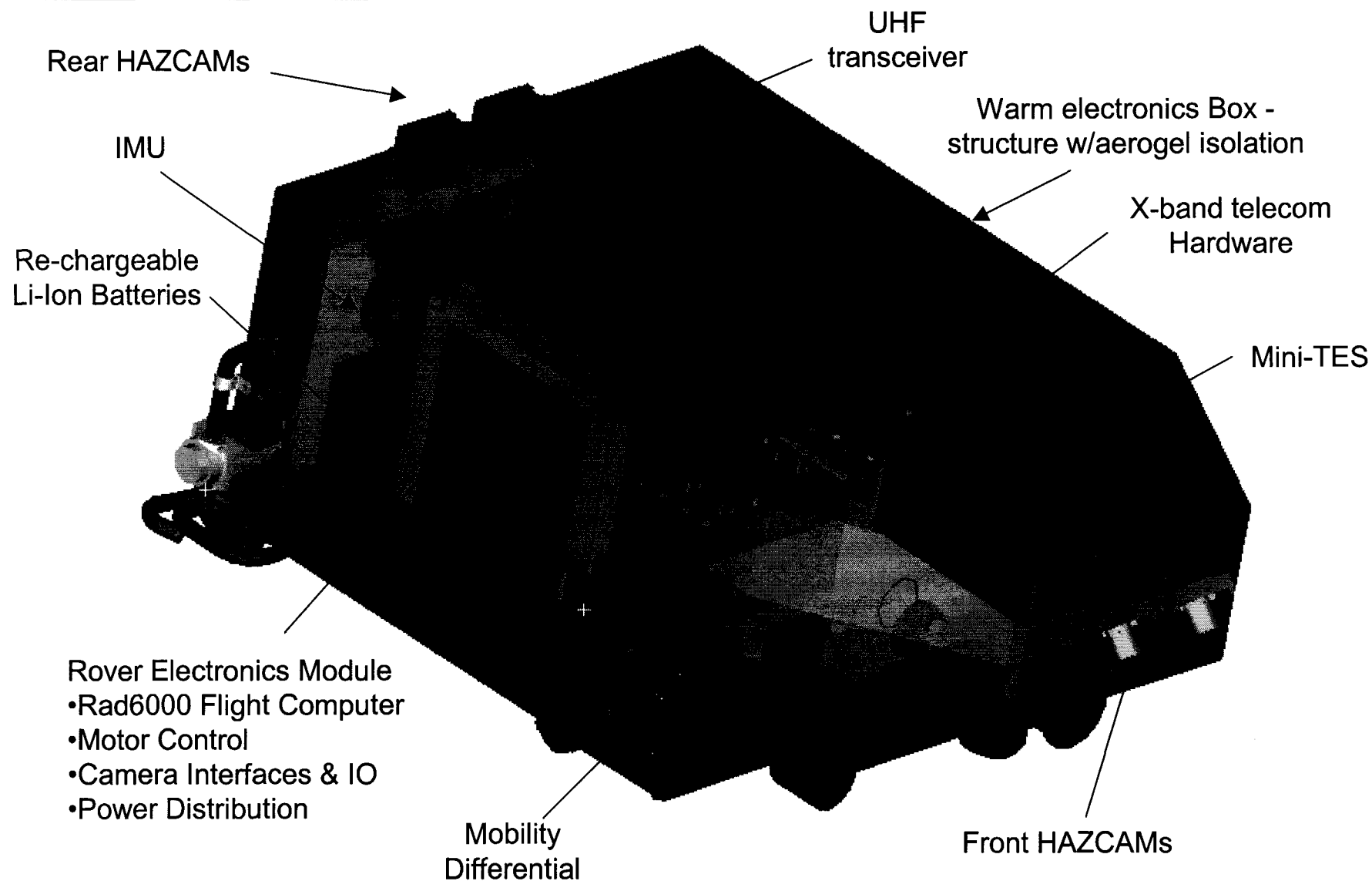
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Rover Warm Electronics Box

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Li Batteries for MER



- **Primary batteries**
 - **For Turn to Entry maneuvers, Entry, Descent and Landing (EDL) operations**
 - **Initial landing operations (Rover regress)**
- **Rechargeable Li ion batteries**
 - **Launch**
 - **Cruise anomalies**
 - **Pyro events**
 - **Surface operations through Sol 90**
- **Thermal Batteries**
 - **Support back shell pyros**



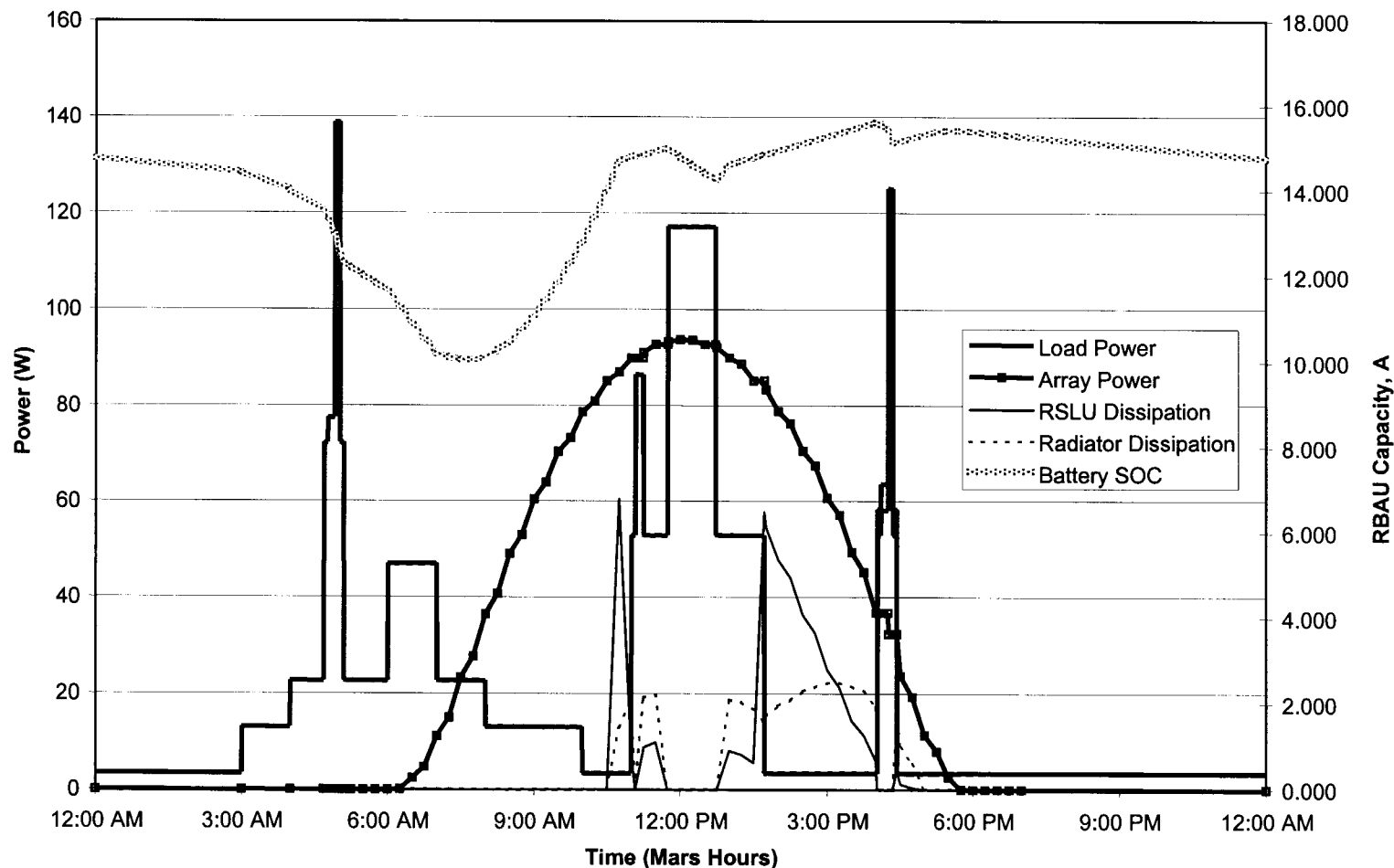
Rover Battery Assembly Unit –Requirements **JPL**

- **Voltage : 24- 36 V (Cruise min. 27 V)**
- **Launch: The power subsystem shall be capable of supplying 200 Whrs during launch, from the switch to internal power until spacecraft separation.**
 - **The battery shall be capable of recycling within 30 minutes after an abort of the first opportunity.**
- **Cruise : Some fault cases may leave the spacecraft in a state where the solar arrays are not illuminated. Power shall be capable, at anytime, during cruise to provide 160 Whrs of energy without solar illumination (to a voltage of 27 V min).**
- **Surface Operations: Capable of operating on the surface of Mars for > 90 Sols.**
- **The Rover RBAU shall be capable of providing 283 Whrs of energy on a single charge.**
- **The Rover RBAU shall be capable of 270 cycles at 50 % DOD at 0° C.**
- **The Rover RBAU shall be capable of return to full charge over a 10 hour period**
- **The Power Subsystem shall assure that the loss of one secondary battery or other BCB will not impact the rest of the S/C.**
- **Each battery in the RBAU shall be capable of firing simultaneous three pyros (each with a load of 7 A) with an interval of at least 100 ms.**



Power Profile for Surface Operations- Sol 90 **JPL**

Energy Balance for MER A, Sol 90 Scenario. Sol 90, Latitude: -15, Tau = 0.5.
Loads: CBE + growth. Energy Balance Margin: 182 Whrs. Min. Battery SOC: 62.9%.





Rover (Rechargeable) Batteries



Criteria for Battery Selection

- **High Specific Energy and Energy Density**
 - $> 100 \text{ Wh/kg}$ and $> 200 \text{ Wh/l}$ at cell level
- **Good Low Temperature Performance**
 - $> 65\%$ of RT capacity available at -20°C @ $\text{C}/5$ to 3.0 V/cell
 - $> 70 \%$ of RT capacity accepted during $\geq 0^\circ\text{C}$ charge at $> \text{C}/10$ to 4.1 V/ cell
- **High Discharge Rate Capability**
 - $> 85\%$ of Low Rate Capacity available at C rate @ 25°C .
- **Long Cycle Life**
 - $> 90 \%$ of the initial capacity at 20°C available after 300 cycles at 50% DOD at 0°C .
- **Good Storageability**
 - $> 85 \%$ of the initial capacity realizable after two years of storage (at $0\text{-}10^\circ\text{C}$ and 50-70% SOC)



Rover (Rechargeable) Batteries-Trade off Studies



| System → Characteristic ↓ | Nickel- Cadmium | Nickel- Hydrogen | Silver-Zinc | Lithium-Ion |
|--|----------------------------|-----------------------------|--------------------|--------------------|
| Specific Energy (Wh/kg) | 25 | 30 | ~100 | >100 |
| Energy Density (Wh/lit) | 100 | 50 | ~150 | >250 |
| Battery Mass for 300Wh MER (kg) | 33 | 28 | 11 | 6 |
| Battery Volume for 300 Wh MER (Lit) | 9 | 17 | 6 | 2.2 |
| Cycle Life (50% DoD) | >1000 | >1000 | <100 | >1000 |
| Wet life (Storageability) | Excellent | Excellent | Poor | Good |
| Self-Discharge (per month) | 15% | 30% | 15-20% | <5% |
| Low temperature Performance (-20°C) | Moderate | Moderate | Moderate | Excellent |
| Temperature Range, °C | -10- 30 | -10- 30 | -10- 30 | -20 to +40 |
| Charge Efficiency % | 80% | 80% | 70% | ~100% |



Rover (Rechargeable) Batteries



Lithium - Ion System

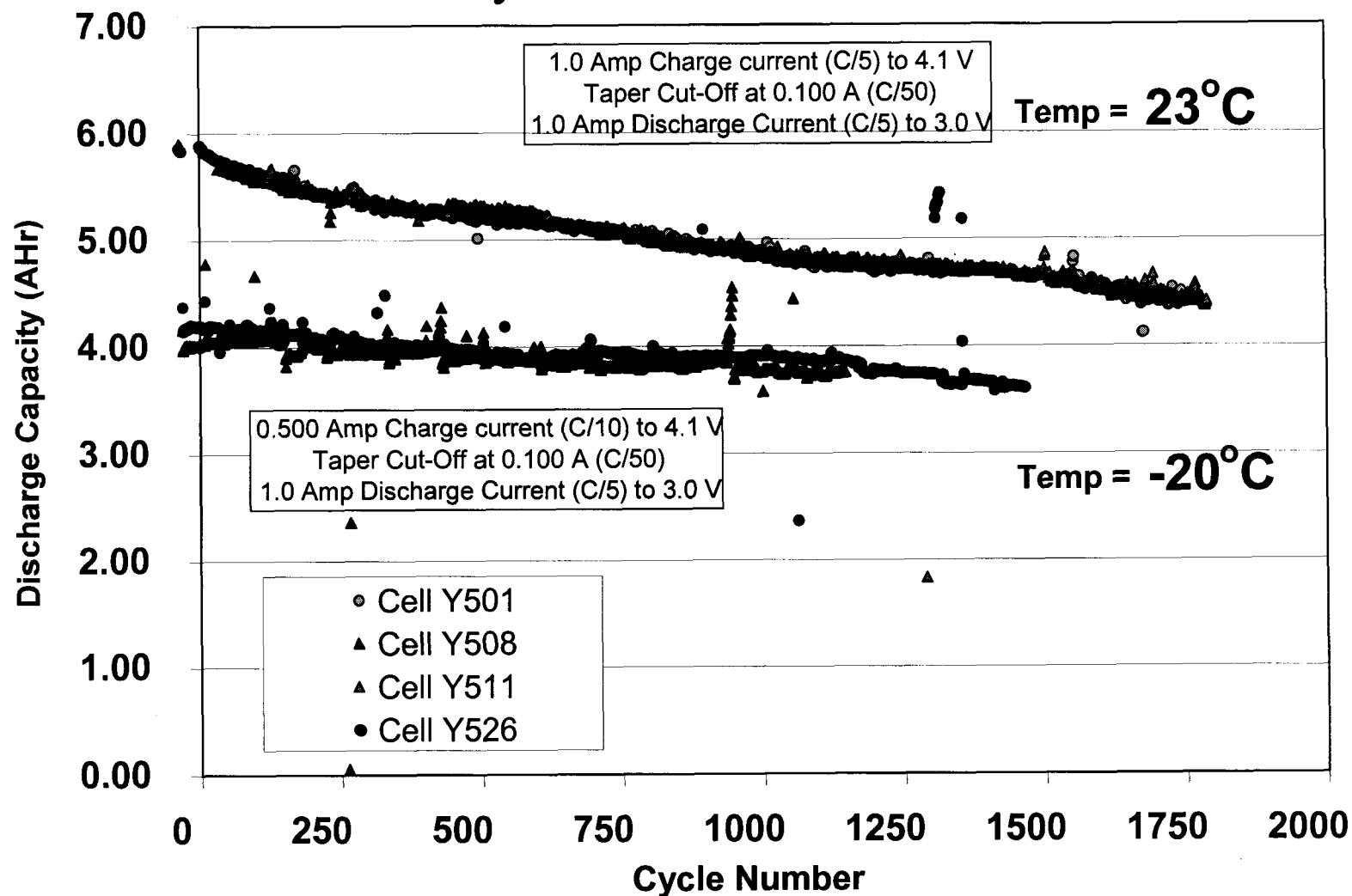
- **Characteristics of Lithium Ion System**
 - High specific energy and excellent energy density
 - Good low temperature performance and high rate capability
 - High coulombic and energy efficiencies
 - low self discharge, good cycle life and storage life
- **Lithium Ion system selected for MER Rover battery**
- **Proposed Battery**
 - Voltage : 32.8 -24 V (after diode)
 - Capacity
 - 16 Ah (BOL) at RT and 14 Ah at 0°C (EOL) or 8.6 Ah at -20°C (EOL)
 - Discharge -Charge Rates
 - C rate discharge (max) during at RT and $< C/2$ at -20°C-30°C.
 - Charge $< C/2$ at 0 to 30°C to 4.1 V/cell minimum of 11 Ah (BOL)
 - 16 Li ion cells of 8 Ah in two parallel strings of 8 cells each.



Yardney Li Ion Cells

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Cycle Life at RT and LT

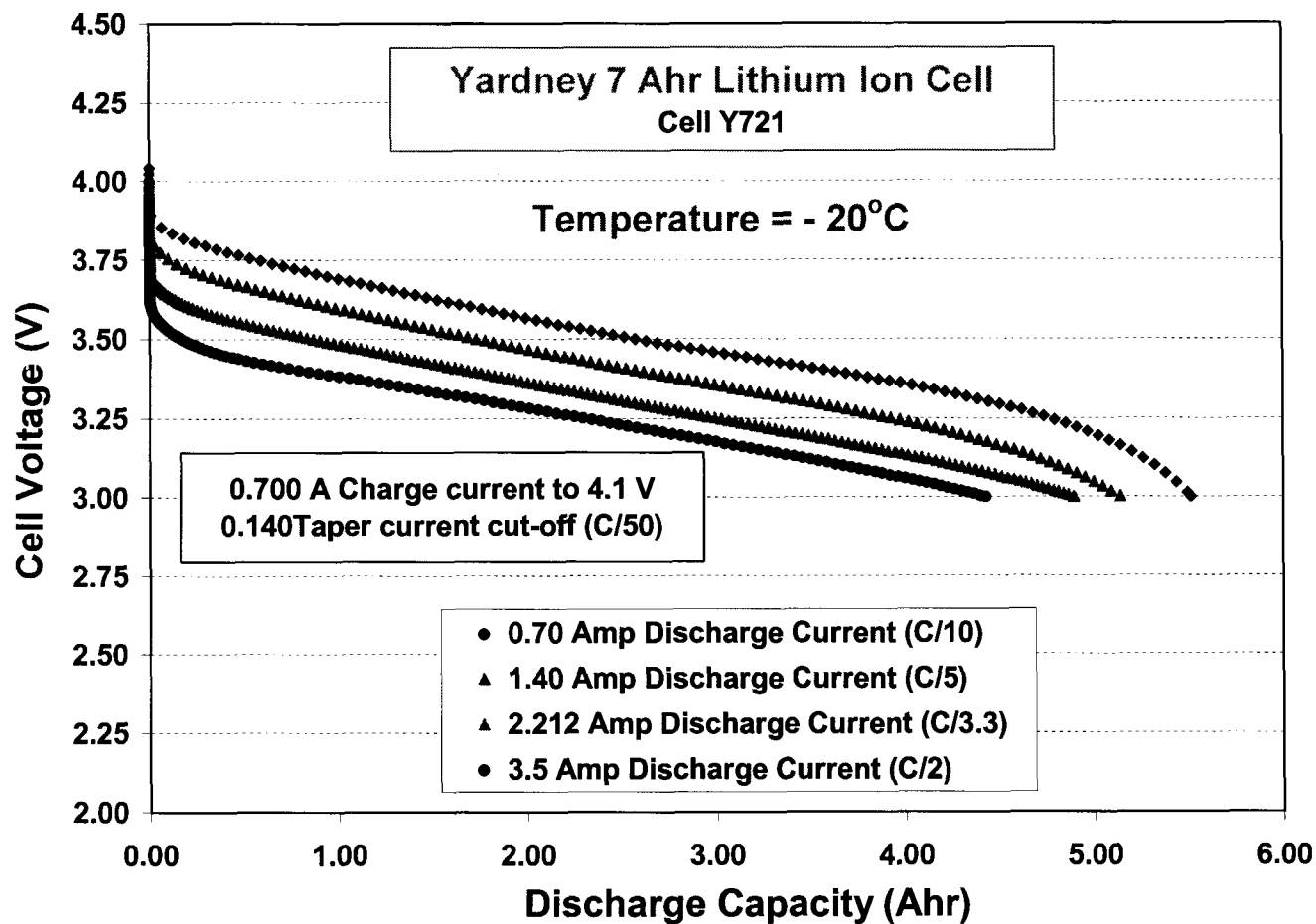




Yardney Li Ion Cells



Low temperature Performance





Yardney Li Ion Cells



Storage Characteristics

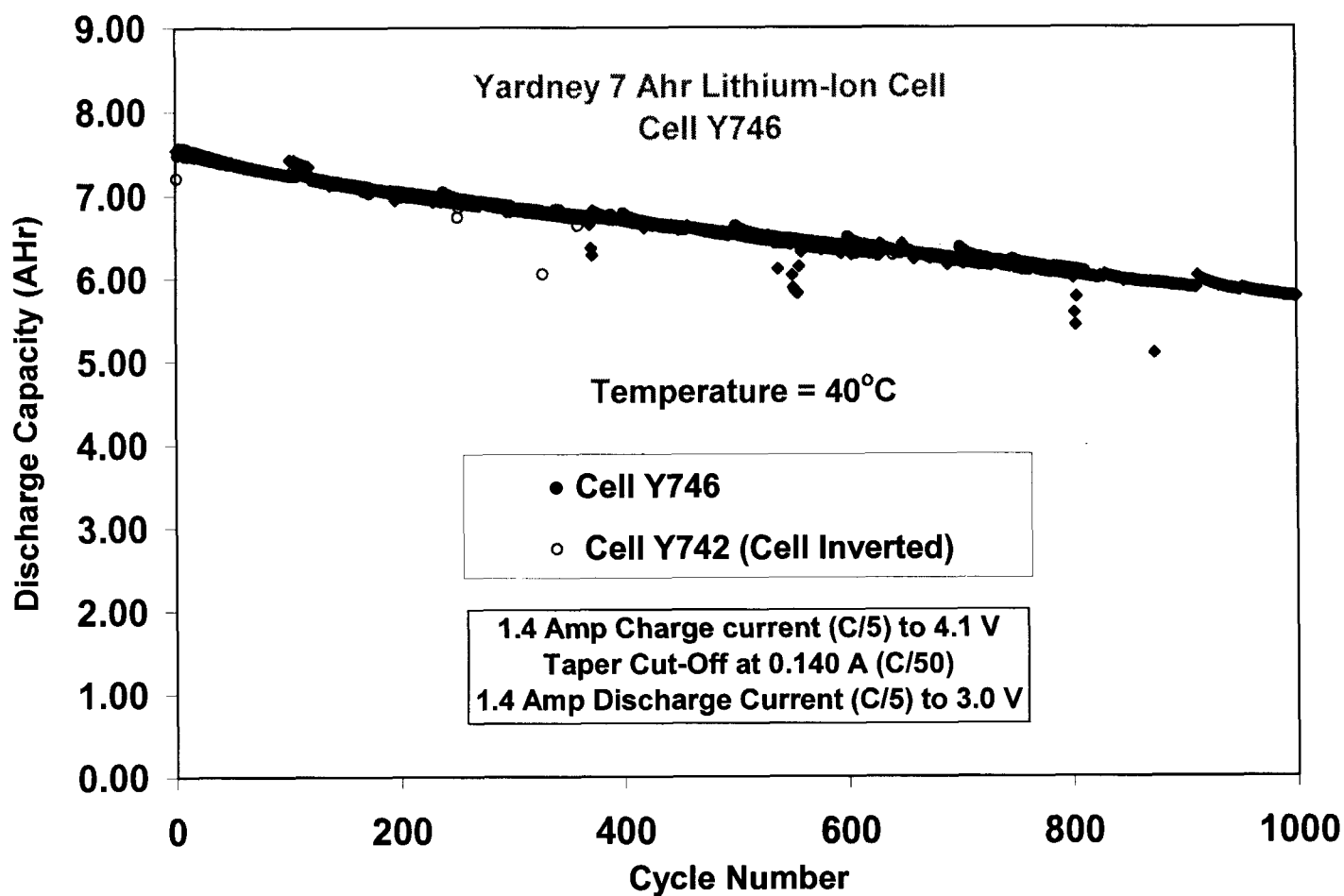
| Cell Number | SOC on Bus | Initial Capacity 23°C (2nd Cycle) | Capacity Prior To Buss Storage at -20°C (2nd Cycle) | Capacity After 2 Years Buss Storage 23°C (6th Cycle) | % of Initial Capacity After 2 Years Buss Storage 23°C | Capacity After 2 Years Buss Storage -20°C (3rd Cycle) | % of Initial Capacity Prior to Buss Storage -20°C |
|-------------|------------|---|---|---|--|--|--|
| Y003 | 30% | 34.0201 | 21.8307 | 33.5936 | 98.7464 | 20.9120 | 95.79 |
| Y004 | 50% | 33.9624 | 22.4870 | 32.8729 | 96.7922 | 20.7299 | 92.19 |
| Y028 | 70% | 33.4789 | ---- | 33.5205 | 100.1242 | 19.2257 | |



Yardney Li Ion Cells

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Effect of Inverted Cell Orientation-100% DOD Cycling at 40°C

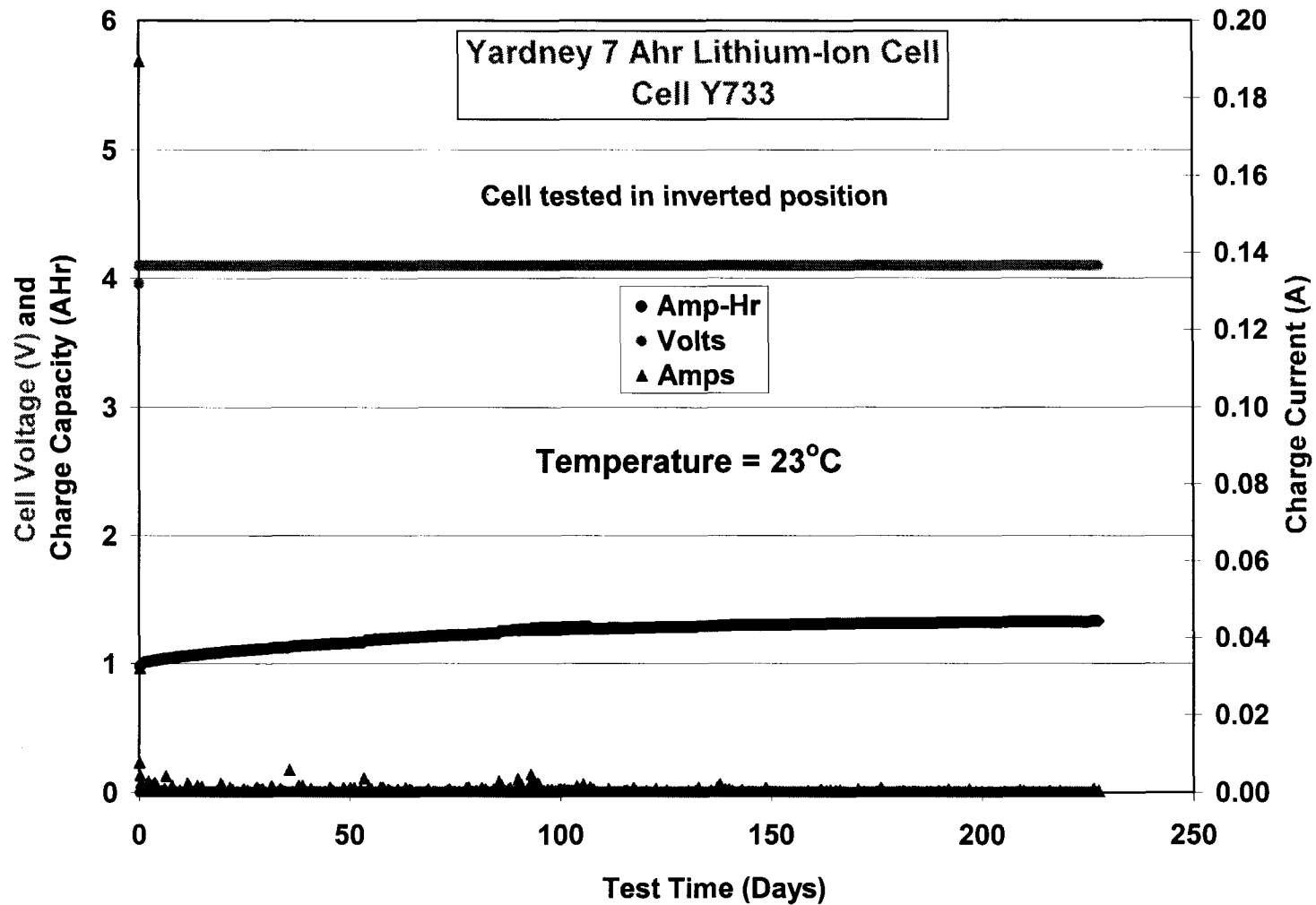




Yardney Li Ion Cells

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Effect of Inverted Cell Orientation- On-buss storage at 4.1 V at 23°C





RBAU Specifications



Cell and RBAU Electrical Specs

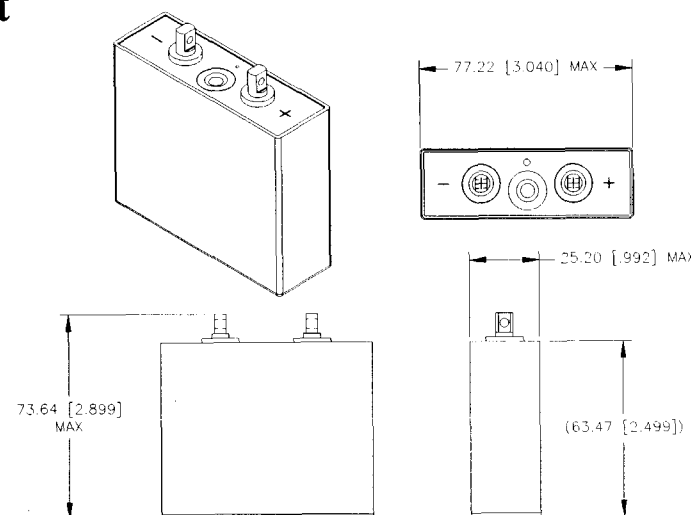
| Test Article | Temperature | Preceding charge | Discharge condition | Capacity (Ah) | Remarks |
|-----------------------|---|-------------------------------------|---------------------|----------------------------|--|
| Cell Capacity (BOL) | 20°C | C/5 to 4.1 (taper) | C/5 to 2.9 V | 10 Ah (min) | Nominal launch |
| | | „ | C/2 to 2.9 V | 9.5 Ah | |
| | | „ | C to 2.9 V | 9 Ah | |
| | 30°C | C/5 to 4.1 (taper) | C/5 to 2.9 V | 10 Ah (min) | Nominal Cruise |
| | 0°C | C/5 to 4.1 (taper) | C/5 to 2.9 V | 8.5 Ah (min) | |
| | -20°C | C/10 to 4.1 (taper) | C/5 to 2.9 V | 6 Ah (min) | |
| | -10°C | C/10 to 4.1 (taper) | C/2 to 3.0 V | 18 Wh (min) | |
| Cycle Life Validation | EOL defined as 2 years storage and 300 cycles; shown by analyses. | | | | |
| Cell Capacity (EOL) | 20°C | C/5 to 4.1 (taper) | C/5 to 2.9 V | 8.5 Ah (min) | Loss of 10% on storage and 12% in 300 cycles |
| | -20°C | C/10 to 4.1 (taper) | C/5 to 2.9 V | 5 Ah (min) | For Surface Ops (280 Wh) |
| | 0°C | C/5 to 4.1 (taper) | C/5 to 2.9 V | 7.0 Ah (min) | |
| RBAU Capacity (BOL) | 20°C | C/10 to 32.4 (taper) or 4.15 V/cell | C/5 to 24 V | 9 Ah (min) on each battery | |
| | -20°C | C/10 to 32.4 (taper) or 4.15 V/cell | C/5 to 24 V | 5 Ah (min) on each battery | |
| | 0°C | C/10 to 32.4 (taper) or 4.15 V/cell | C/5 to 24 V | 7 Ah (min) on each battery | |
| | 30°C | C/10 to 32.4 (taper) or 4.15 V/cell | C/5 to 24 V | 9 Ah (min) on each battery | |
| | -10°C | C/10 to 31 (taper) or 3.875V/cell | C/2 to 27 V | 160 W h (min) on the RBAU | Cruise –little margin |



The Cell Design



- The cell is a true prismatic Lithium Ion cell. True prismatic design offered improved fit into the envelope combined with superior thermal pathways.
- The cell used the same chemistry as was optimized for the MSP01 Lander.
 - This chemistry was originally developed at Yardney under the U.S. Air Force PRDA Contract
 - All purpose chemistry with performance from -40°C (discharge and charge) to 60°C.
 - Supports up to a 7C continuous discharge rate.
 - Cell also utilized much of the physical cell design proven in under the MSP01 program
 - Time frame necessitated a low risk approach.

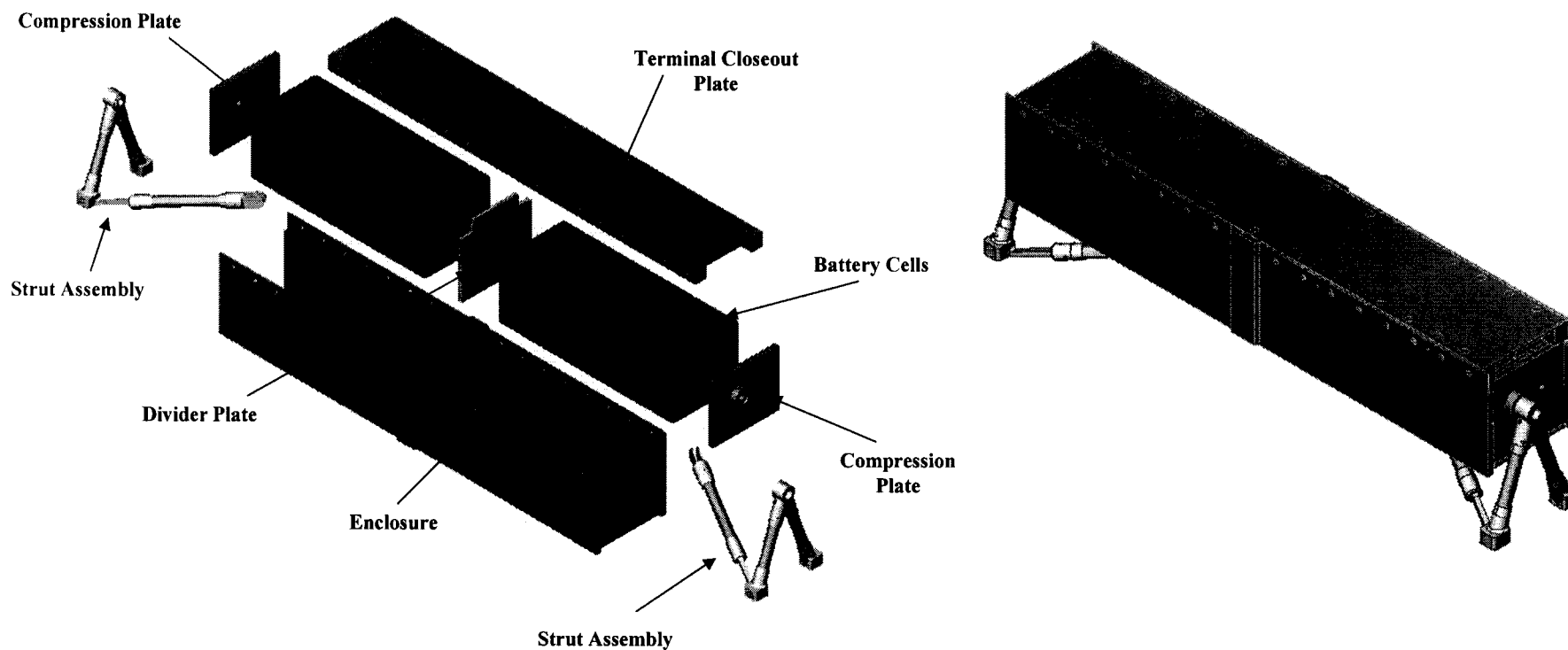


Mass: 295 grams

Volume: 123 cm³



The RBAU Design

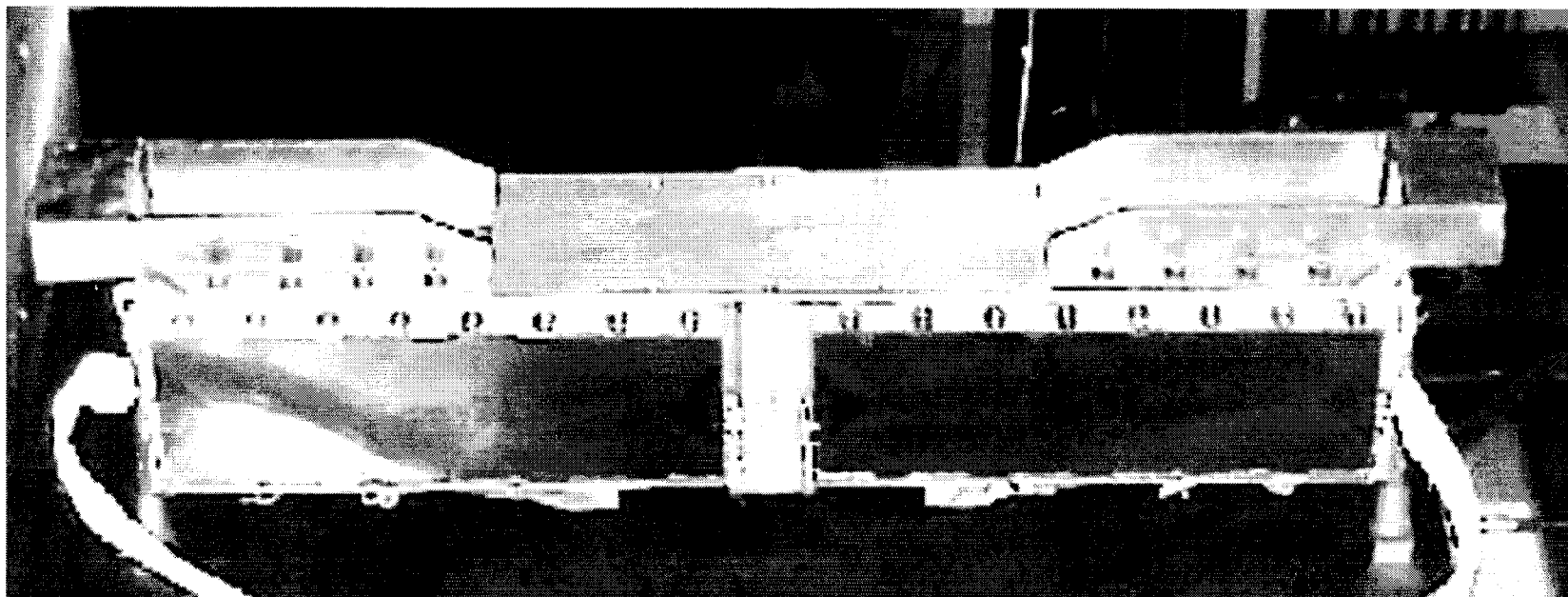


- **Two parallel batteries each with eight Li ion cells in series - 30 V, 16 Ah (480 Wh)**



The RBAU Design

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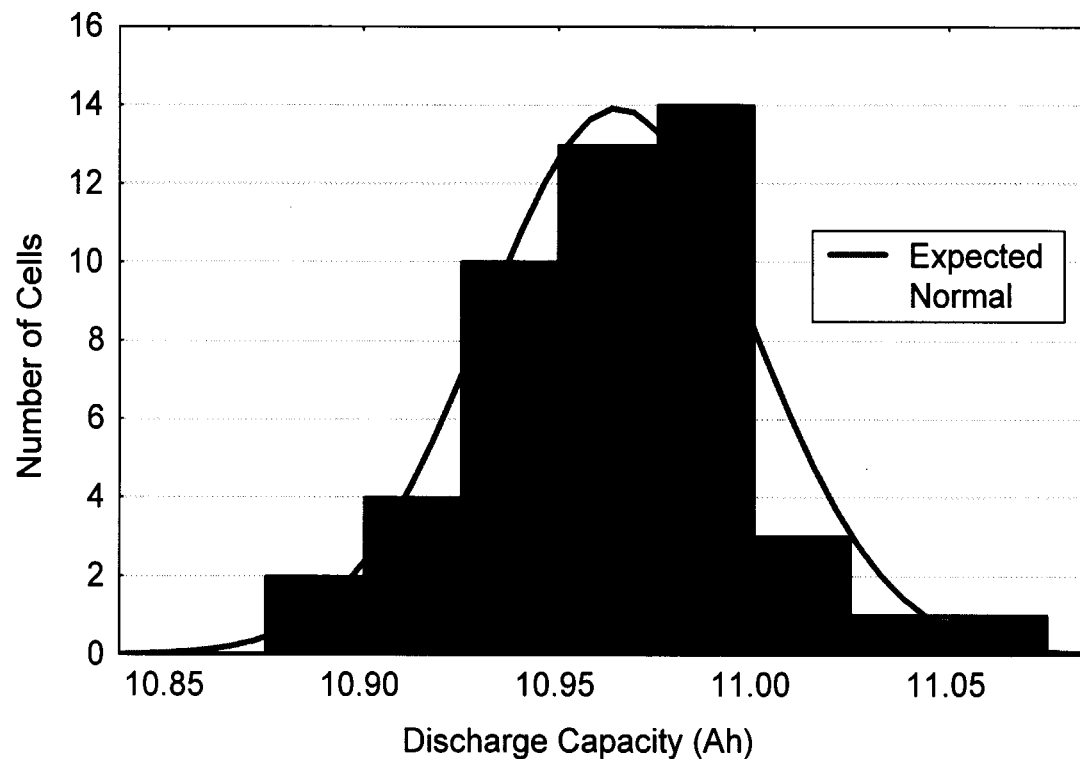




Cell Electrical Testing-Typical Results



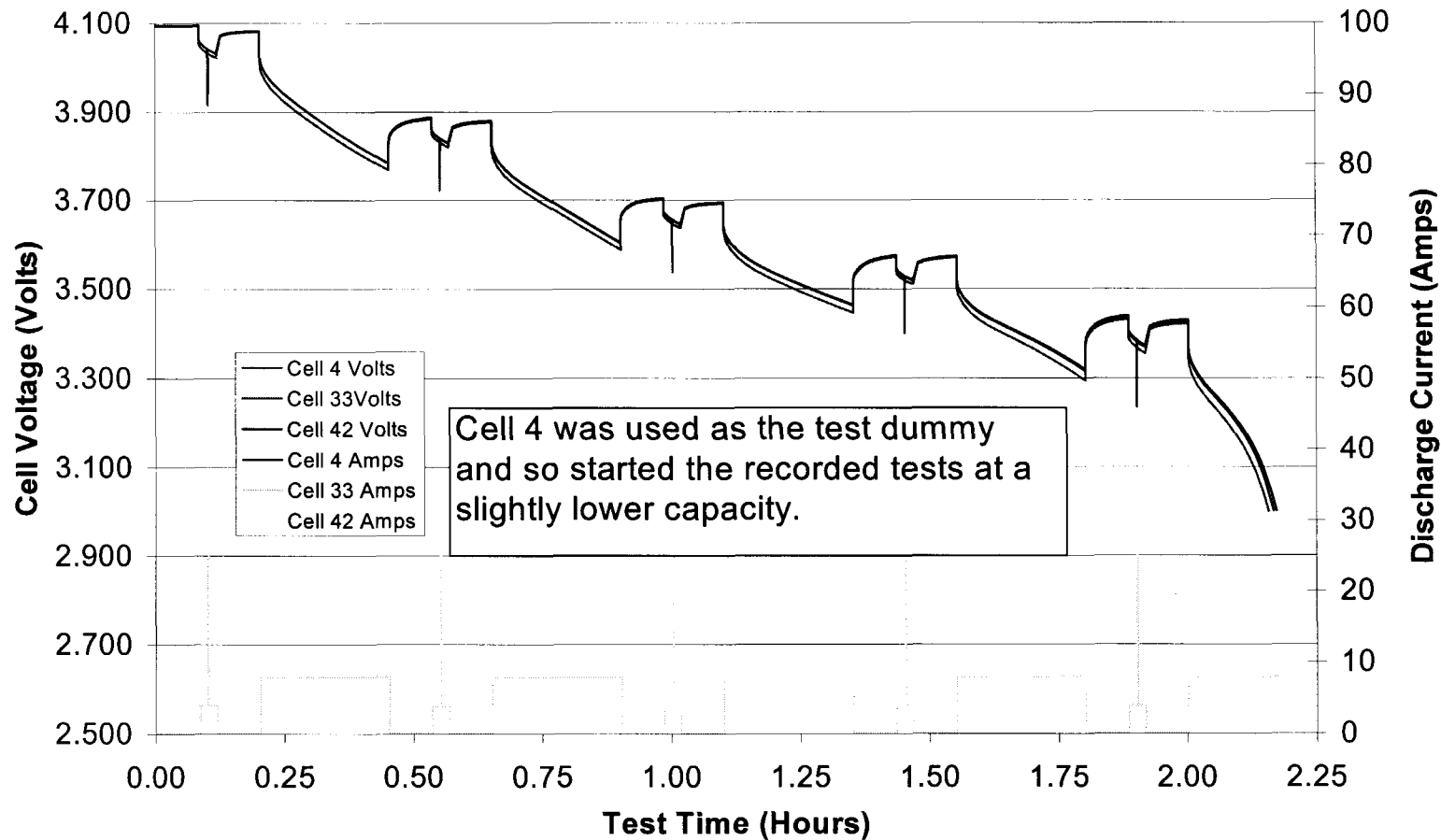
- The electrical testing of the cells showed a very tight cell to cell distribution
 - Entire Qualification build was less than $\pm 1\%$





Pulse Capability of the Cells

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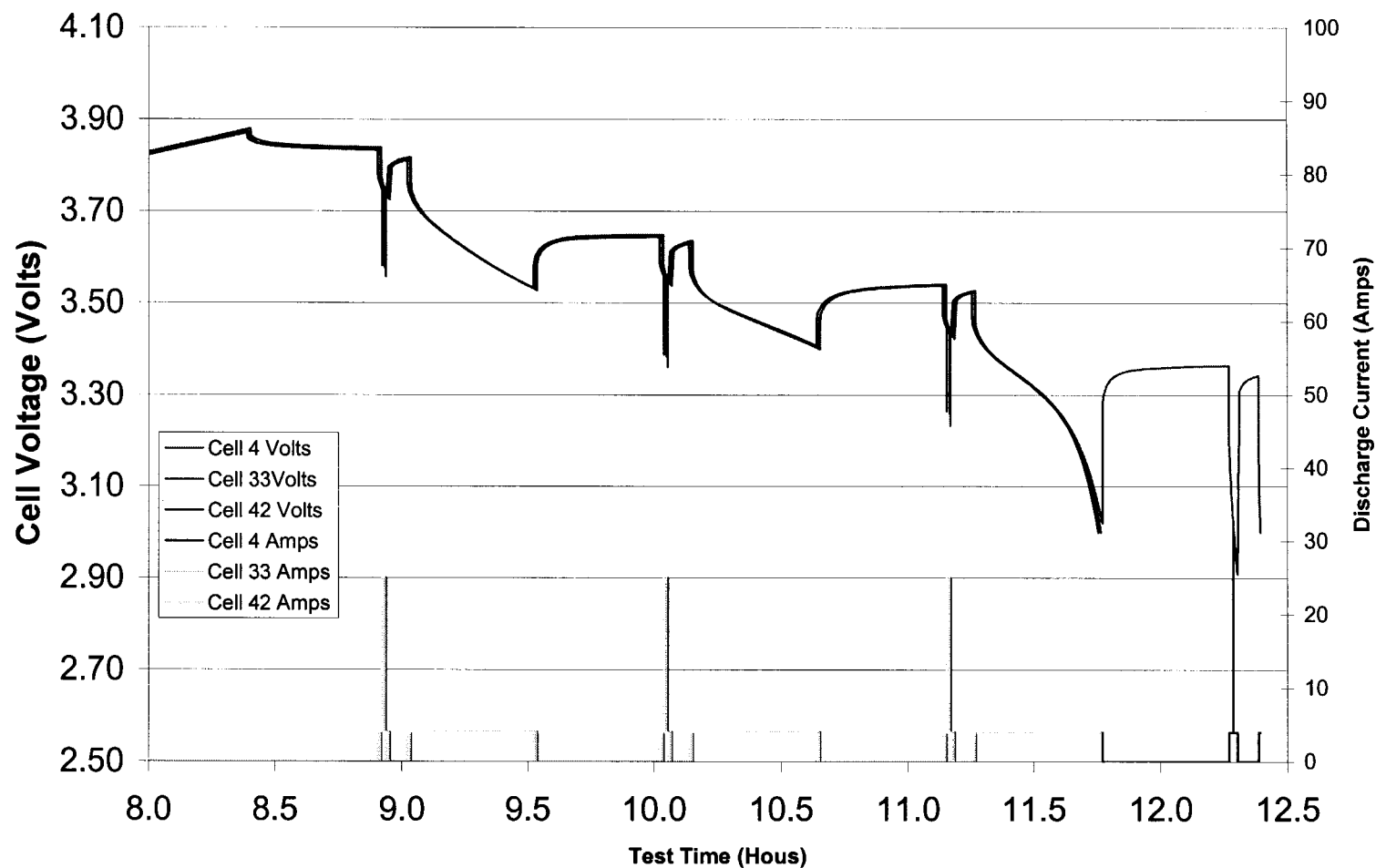


- **20°C Requirement met at 100% of Charge and with 8Ah of capacity removed.**



Pulse Capability of the Cells

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- Cells were charged, at 0°C, at C/5, to 3.875 without a taper. Cells meet the requirement with 4 Ah removed.
 - This translates into a Cell OCV of 3.54 which corresponds to 35% SOC



Electrical Testing-Cell Selection



- **Cell selection consisted of two phases**
 - Phase 1 was the removal of any cell that was not within $\pm 2.5\sigma$ on any process data or test.
 - The cells were then evaluated under an 8 criteria cell selection process.

| | |
|--------------------------|---------------------------|
| 1.) C/5 @ 20 °C (Ah) | 2.) C/5 @ -20 °C (Ah) |
| 3.) C/2 @ -10 °C (Ah) | 4.) C/10 @ -20 °C (Time) |
| 5.) C/5 @ 20 °C (Time) | 6.) -20°C Rate Capability |
| 7.) 20°C Rate Capability | 8.) Self Discharge Rate |
- **Each of the 8 parameters underwent a weighting procedure based upon the amount that each cell varied from the mean.**
 - A cell at nominal received a perfect score.
 - Variation from nominal decreased the score at the square of the amount of deviation.
- **Each score was then multiplied by the weighting factor.**
 - Weighting emphasis toward self discharge and charge times as ability to balance cells during mission was (is) uncertain.



Electrical Testing-Cell Selection

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- Results: FM5 Battery 1**

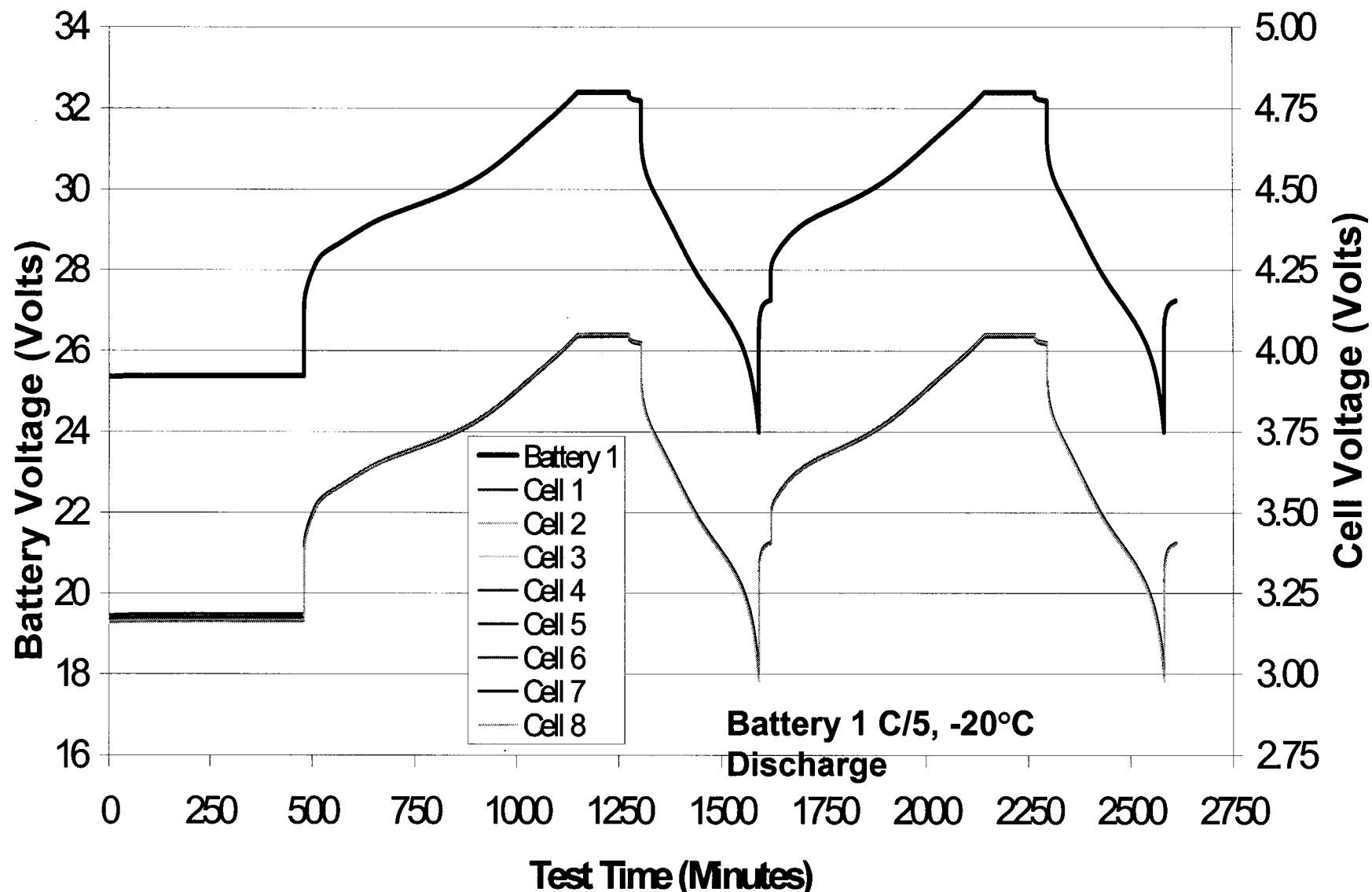
| CELL ID | STAND | time_20 | time_n20 | C5_20A | N20_Rate | P20_rate | C2_N10A | C5_N20A |
|------------------|--------------|----------------|-----------------|---------------|-----------------|-----------------|----------------|----------------|
| Cell 1 | 6.104 | 6.994 | 11.790 | 10.634 | 0.775 | 0.965 | 8.890 | 8.526 |
| Cell 2 | 6.409 | 7.035 | 11.817 | 10.689 | 0.772 | 0.964 | 8.899 | 8.510 |
| Cell 3 | 6.104 | 6.987 | 11.743 | 10.618 | 0.771 | 0.964 | 8.841 | 8.456 |
| Cell 4 | 6.104 | 7.008 | 11.830 | 10.644 | 0.774 | 0.965 | 8.879 | 8.496 |
| Cell 5 | 5.951 | 6.999 | 11.798 | 10.641 | 0.769 | 0.963 | 8.839 | 8.476 |
| Cell 6 | 6.104 | 6.994 | 11.769 | 10.648 | 0.769 | 0.963 | 8.846 | 8.459 |
| Cell 7 | 6.104 | 7.004 | 11.747 | 10.648 | 0.774 | 0.964 | 8.875 | 8.493 |
| Cell 8 | 5.951 | 7.017 | 11.816 | 10.665 | 0.770 | 0.963 | 8.878 | 8.501 |
| AVERAGE | 6.104 | 7.005 | 11.789 | 10.649 | 0.772 | 0.964 | 8.868 | 8.490 |
| STDEV | 0.141 | 0.015 | 0.033 | 0.021 | 0.003 | 0.001 | 0.023 | 0.024 |
| RANGE (±) | 3.85% | 0.35% | 0.37% | 0.33% | 0.45% | 0.15% | 0.34% | 0.41% |

- The 3.85% variation on the stand is multiplied by a factor of 1000 to be comparable. (Actual difference is <0.0005 V)**



Electrical Testing-RBAU Results

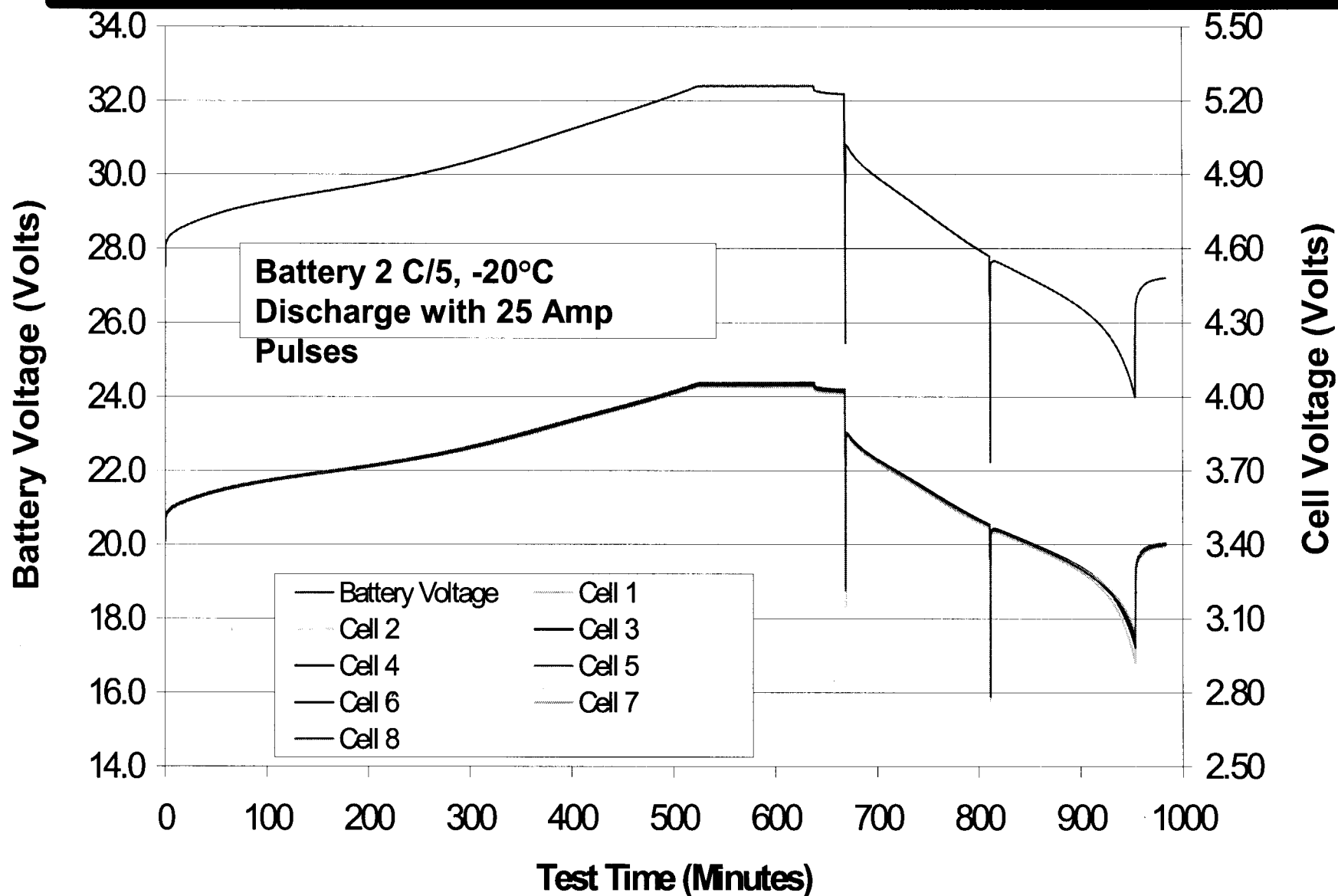
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Electrical Testing-RBAU Results

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RBAU Testing (2003 MER Program)



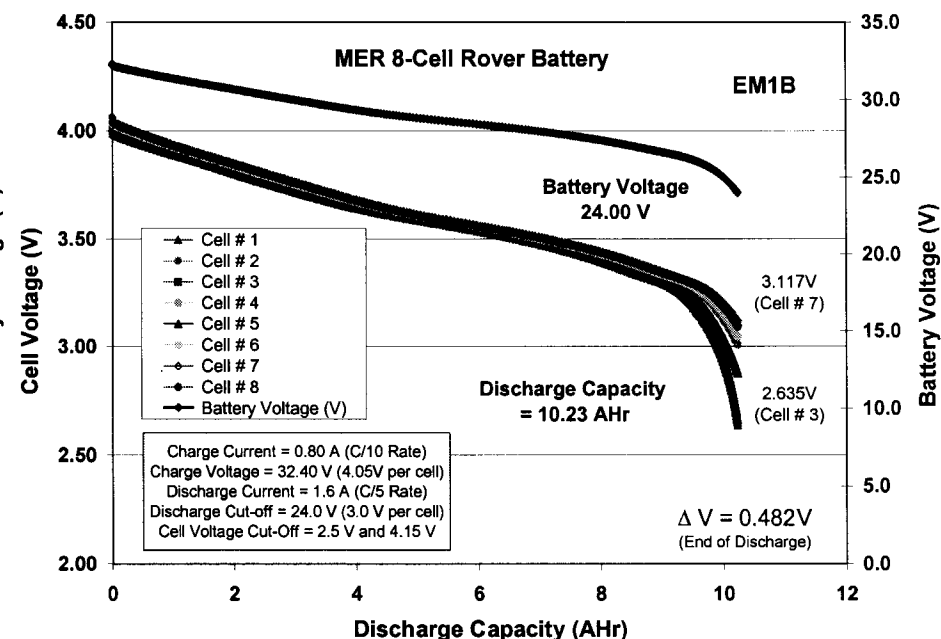
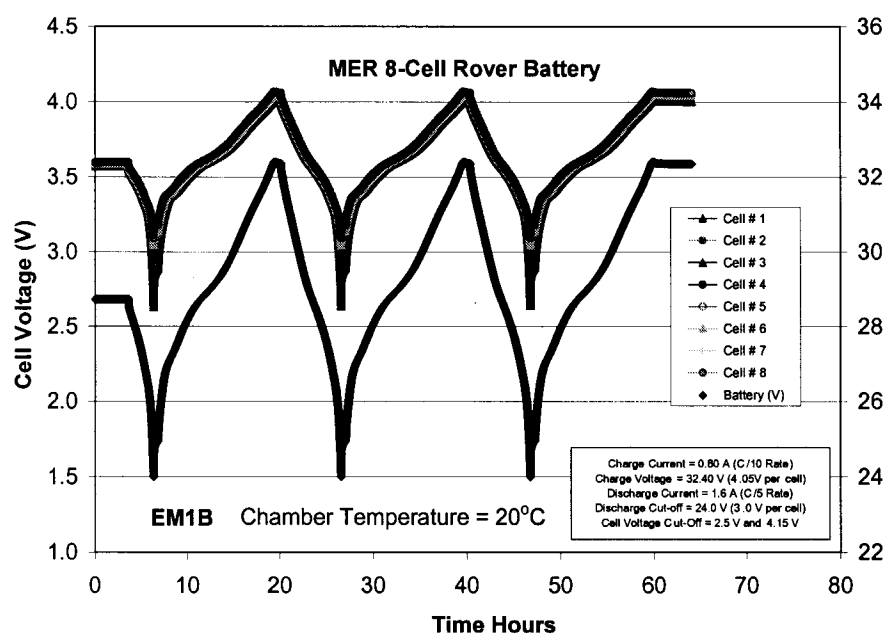
- **EM1 RBAU**
 - Acceptance Testing
 - Cruise Operation
 - EDL Operation (No pulsing)
 - Mission Surface Operation Simulation (~ 2 months of testing)
- **EM2 RBAU**
 - Acceptance Testing
- **FM1 RBAU**
 - Acceptance Testing
- **FM3 RBAU**
 - Acceptance Testing
- **Mission Simulation Battery (in transport)**
- **Acceptance Testing**
 - 3 Cycles at 20°C (C/5 Rate, charged to 32.4V)
 - 72 Hour OCV Stand (Battery Fully Charged to 32.4V)
 - 3 Cycles at - 20°C (C/5 Rate, charged to 32.4V)



MER RBAU Engineering Module



Initial Characterization/Conditioning at 20°C

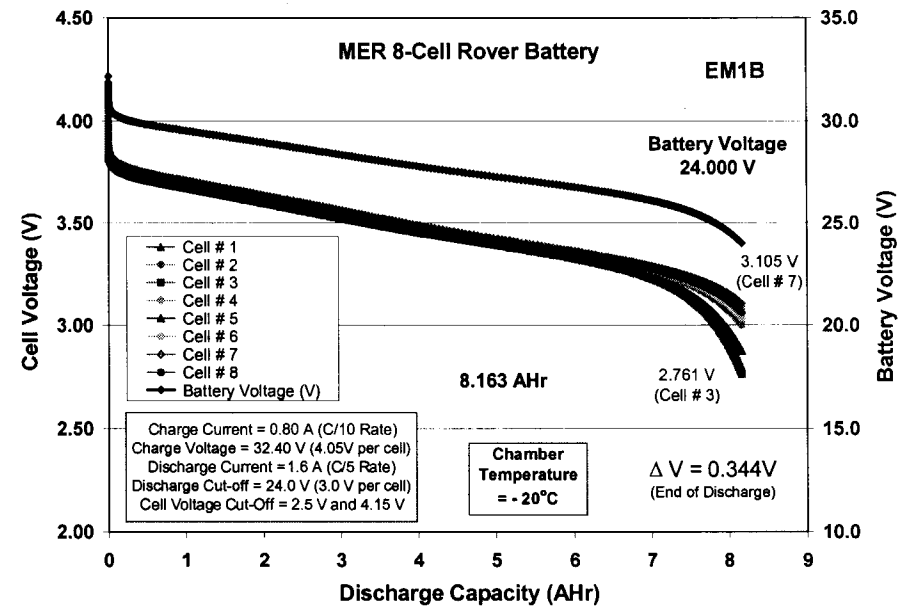
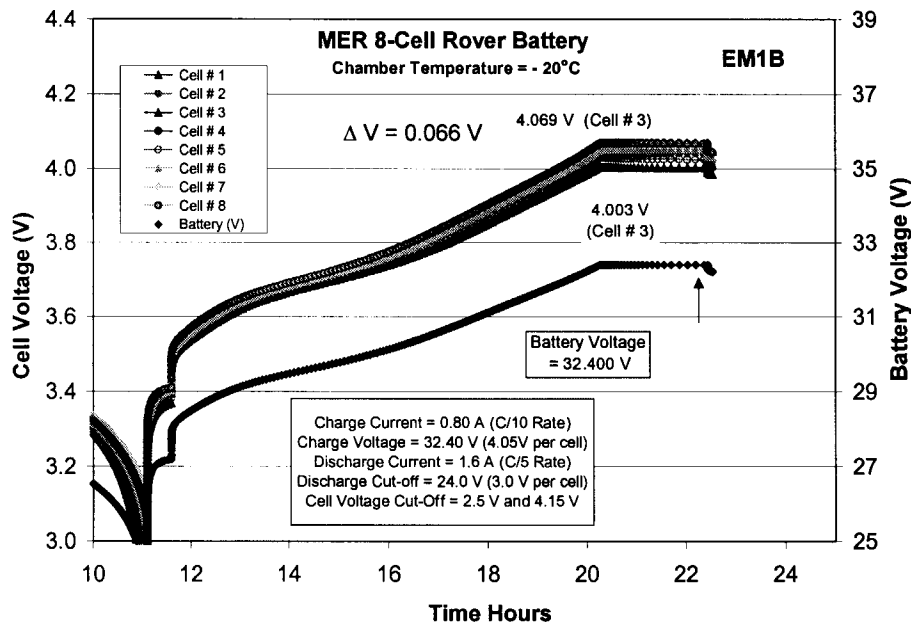




MER RBAU Engineering Module



Initial Characterization/Conditioning at -20°C

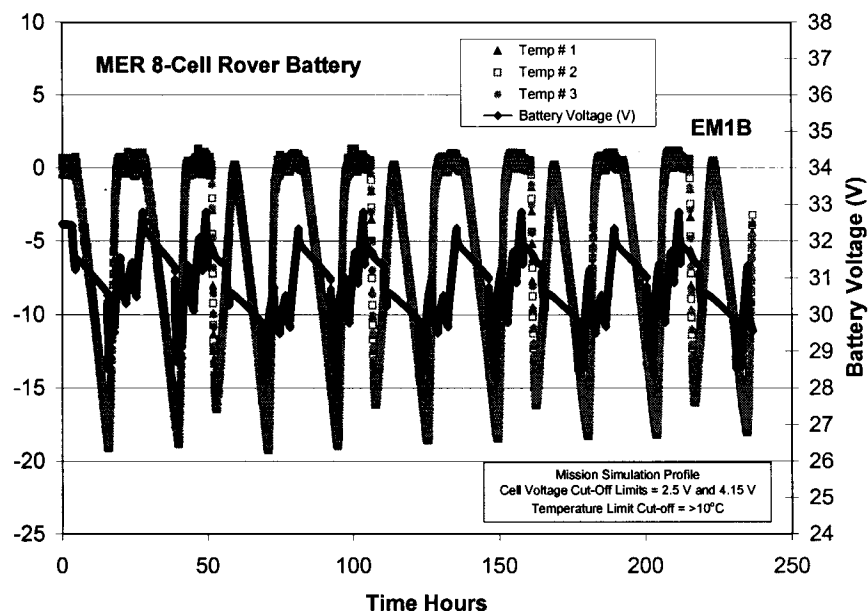
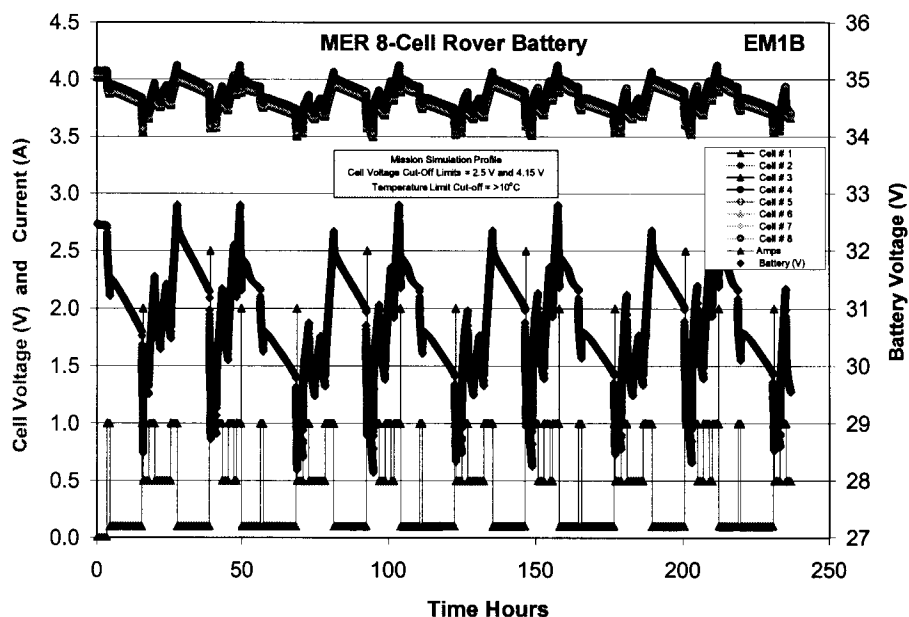




MER RBAU Engineering Module



Mission Simulation Testing SOLS 1-8

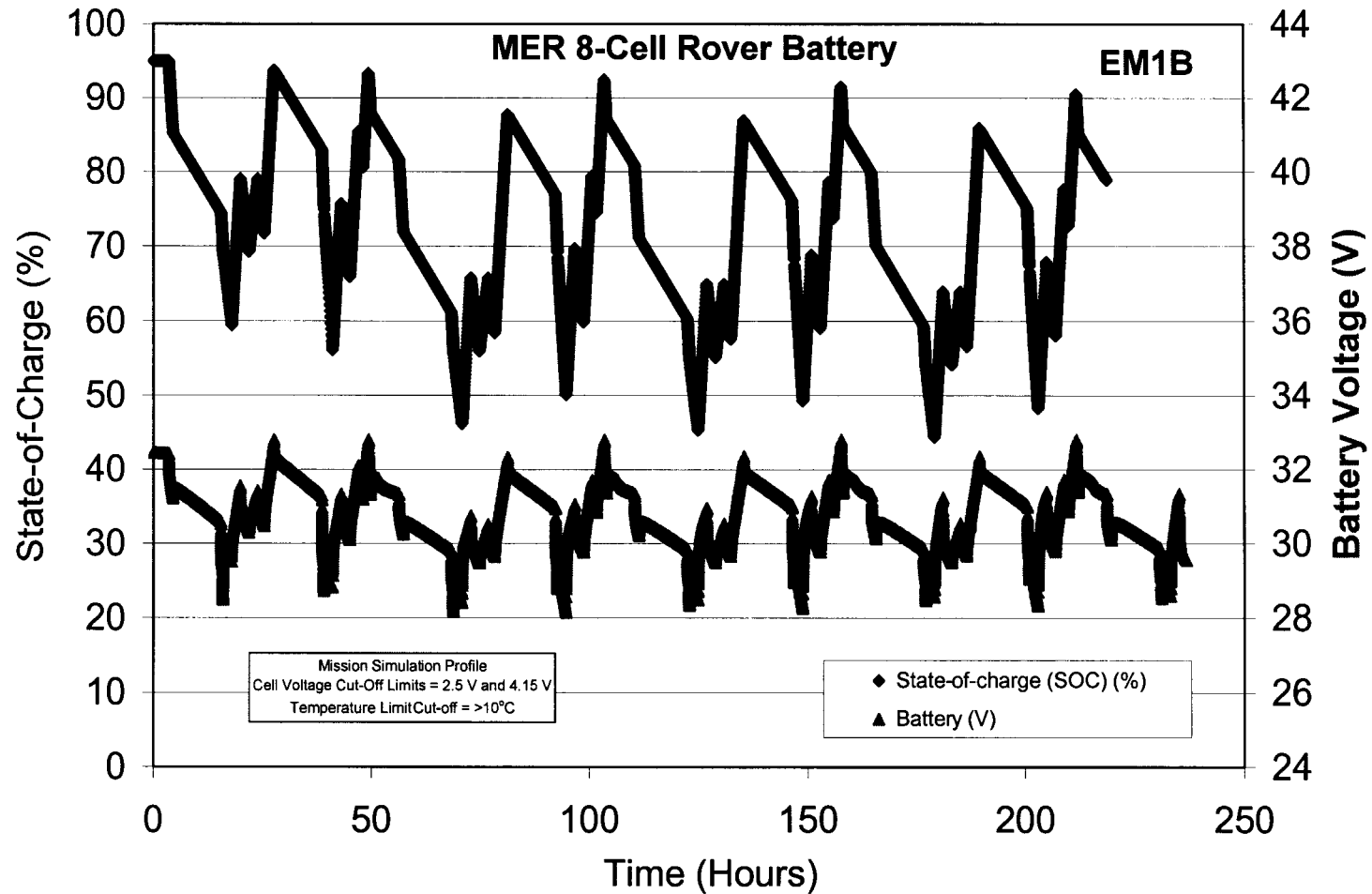




MER RBAU Engineering Module



Mission Simulation Testing SOLS 1-8





Battery Control Board

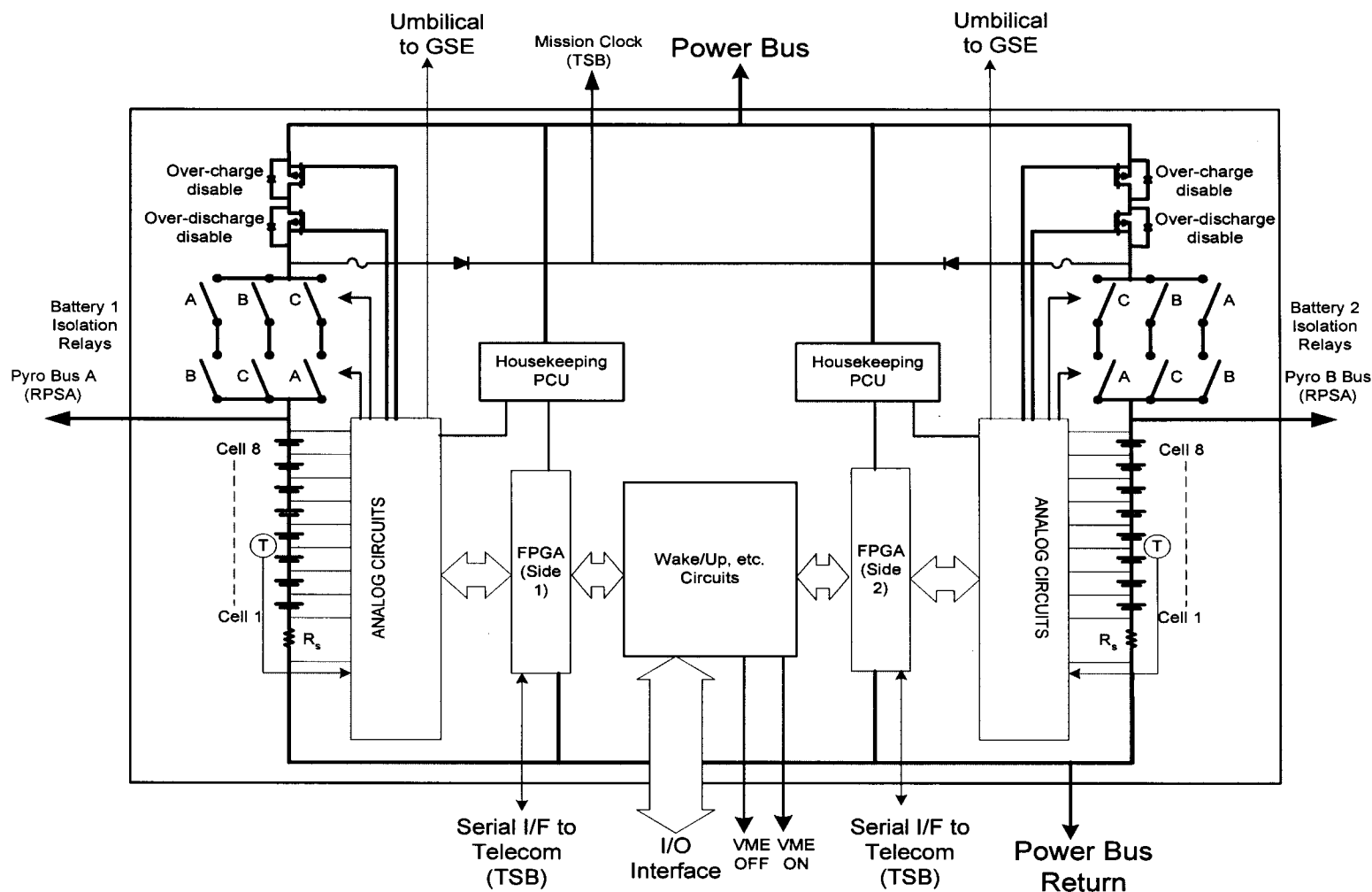
Main Functional Requirements



- **Monitors all of the critical power analog telemetry signals in the Rover**
 - **Rover solar array Voc**
 - **Rover solar array Isc**
 - **Bus voltage**
 - **Rover solar array current**
 - **Rover shunt current**
 - **Lander bus current (bi-directional)**
 - **Cruise bus current (bi-directional)**
 - **RPDU current**
 - **Rover battery voltage**
 - **Rover battery cell voltages (8 per battery)**
 - **Rover battery current (1 per battery)**
 - **Rover battery temperatures (5)**
 - **3 internal, 1 battery case temperature, and routes 1 through umbilical**
 - **Measures and stores critical night time measurements**
 - **REM temp., SSPA LHP radiator inlet temp., Pan Cam CCD PRT**



BCB: High Level Block Diagram





Battery Management



- Terminology Definitions

- V_{cmd} ($V_{command}$) = V_{sc} ($V_{stop\ charge}$) = one of four prog levels (3.85, 3.95, 4.15, 4.20V)
- V_{bp} (V_{bypass}) = $V_{cmd} - 30mV$
- V_{ebp} ($V_{end\ bypass}$) = $V_{cmd} - 70mV$
- V_{ch} (V_{charge}) = $V_{cmd} - 150mV$
- V_d ($V_{discharge}$) = 3.4V
- V_{sd} ($V_{stop\ discharge}$) = 2.9V



Battery Management (cont.)

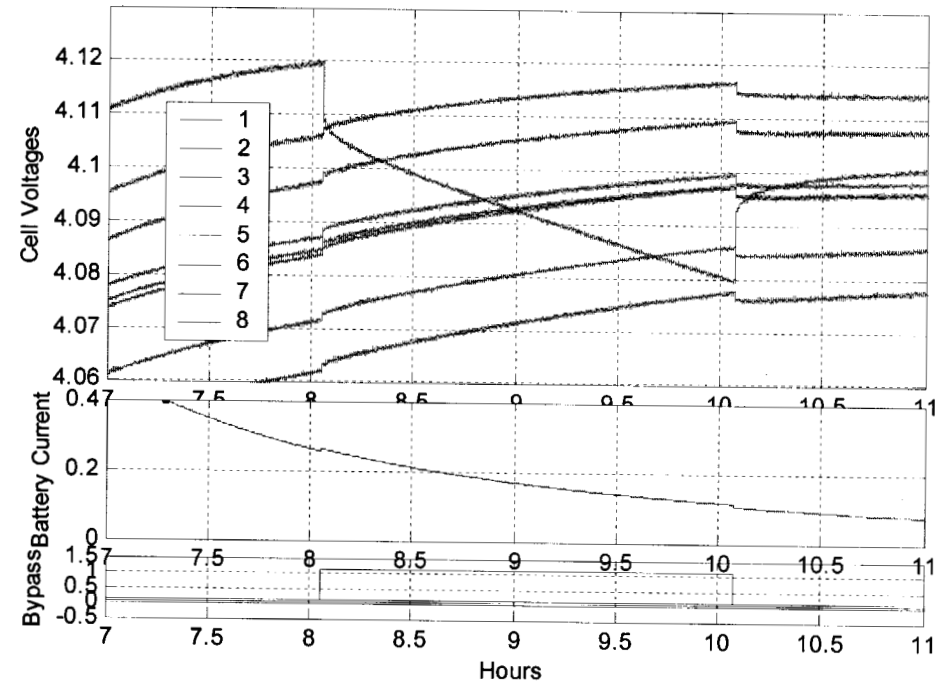
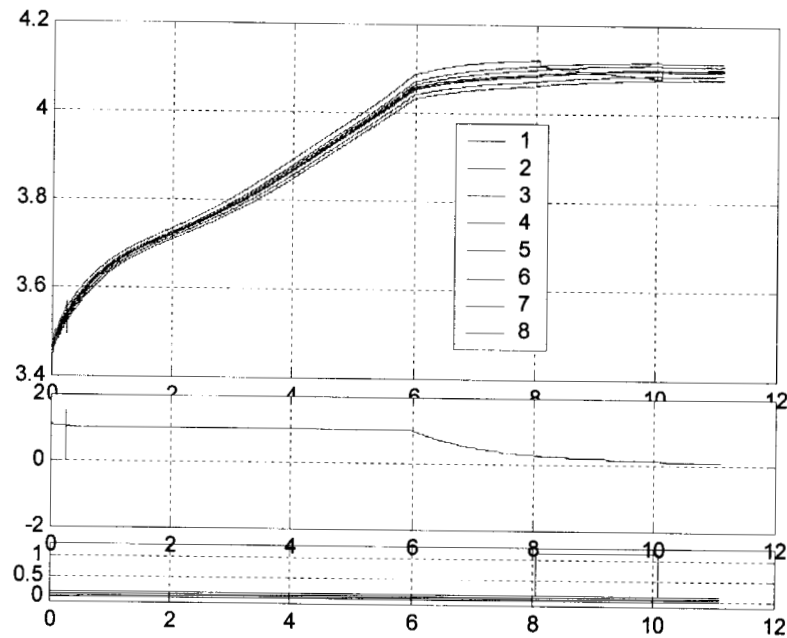


- Charge control
 - Stop Charge (open charge FET) if:
 - Any cell is greater than or equal to V_{cmd}
 - All cells are above V_{bp}
 - Charge rate is greater than 1C
 - Any cell is $<1V$ and the battery is $>20V$.
 - Start Charge (close charge FET) if:
 - All cells are below V_{ch}
 - After POR
 - Stop Discharge (open discharge FET) if:
 - Any cell is less than or equal to V_{sd}
 - Discharge rate exceeds 2C (latchoff, ground only)
 - Start Discharge (close discharge FET) if:
 - All cells are above V_d .
- Charge Balancing
 - Start cell bypassing at or above V_{bp}
 - Stop cell bypassing at or below V_{ebp}



BCB/Battery Lab Results

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LI BATTERIES ON 2003 MARS EXPLORATION ROVER JPL

Summary

- **The 2003 Mars Exploration Rovers (MER) have Li-SO₂ primary batteries on the Lander to support the EDL operations, Li-FeS₂ thermal batteries on the back shell for firing pyros during cruise stage separation and Li ion rechargeable batteries on the Rover to assist in the launch, TCM and surface operations.**
- **The Rover is about ten times bigger in size, pay load and traversing capability than the previous Sojourner rover and will have a longer mission life with the rechargeable batteries.**
- **Lithium ion batteries fabricated by Yardney Technical Products for the MER mission show adequate performance in the operating range, in the MER environments, under steady state and pulse currents and, also in conjunction with a battery charger designed and built in-house.**



Acknowledgements

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